

# Radio observations of the cool gas, dust, and star formation in the first galaxies

C. Carilli (NRAO), F. Walter (MPIA), R. Wang (NRAO/Arizona), D. Riechers (CIT), J. Wagg (ESO), X. Fan (Arizona), K. Menten (MPIfR), F. Bertoldi (Bonn), P. Cox (IRAM)

## Abstract.

We summarize cm through submm observations of the host galaxies of  $z \sim 6$  quasars. These observations reveal the cool molecular gas (the fuel for star formation), the warm dust (heated by star formation), the fine structure line emission (tracing the CNM and PDRs), and the synchrotron emission. Our results imply active star formation in  $\sim 30\%$  of the host galaxies, with star formation rates  $\sim 10^3 M_\odot \text{ year}^{-1}$ , and molecular gas masses  $\sim 10^{10} M_\odot$ . Imaging of the [CII] emission from the most distant quasar reveals a 'maximal starburst disk' on a scale  $\sim 1.5$  kpc. Gas dynamical studies suggest a departure of these galaxies from the low- $z$   $M_{BH} - M_{bulge}$  relation, with the black holes being, on average, 15 times more massive than expected. Overall, we are witnessing the co-eval formation of massive galaxies and supermassive black holes within 1 Gyr of the Big Bang.

**Keywords:** First Stars and Galaxies: Challenges in the Next Decade, AIP, 2010

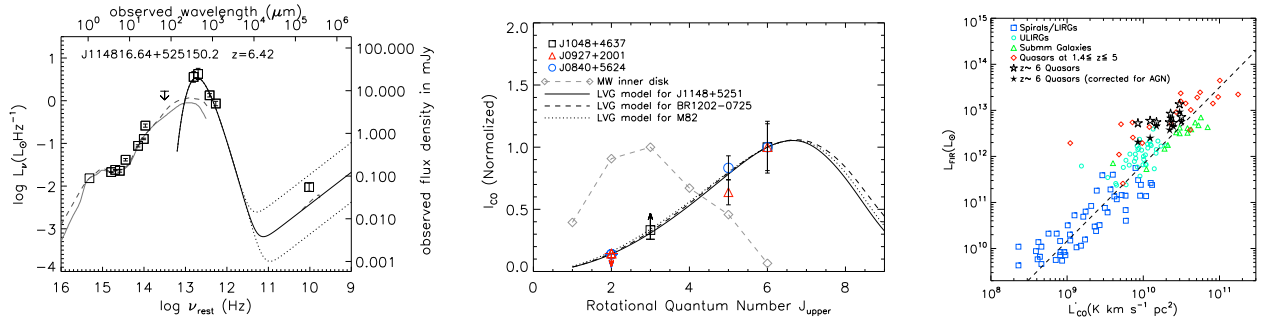
**PACS:** 98.54

## Quasar host galaxies at $z \sim 6$

Remarkable progress has been made in the study of galaxies back into cosmic reionization, or 'first new light' in the Universe ( $z \geq 6$ ), at optical through near-IR wavelengths. However, such observations are limited to the stars and ionized gas, the products of star formation in galaxies. Recent radio observations have begun to probe the 'other half' of the story, namely, the cool gas and dust, the fuel for star formation in galaxies, as well as star formation itself, unhindered by obscuration. We summarize these recent observations, and discuss the dramatic increase in potential with the EVLA and ALMA.

Radio studies of the first galaxies have focused primarily on the host galaxies of luminous quasars, for a number of (mostly practical) reasons. First, the number of  $z \geq 6$  quasars has increased dramatically in the last decade through the SDSS and UKIDSS surveys (Fan et al. 2006, Willott et al. 2010). Second, quasars are the only population of such extreme  $z$  galaxies with spectroscopic redshifts (with one exception), as required for molecular line follow-up observations give current bandwidth limits. And third, quasar demographics, as well as the black hole – bulge mass relation, suggest that these are massive (proto-)galaxies, and current radio telescopes can only detect the more massive galaxies at such high redshifts. The black hole masses in these systems are  $\sim 10^9 M_\odot$ , implying bulge masses  $\sim 10^{12}$ , based on the low- $z$  relation (Häring & Rix 2004).

Study of very early massive galaxy formation has become topical with the recent evidence suggesting that massive galaxies form most of their stars early and quickly, and the more massive, the earlier and quicker. Evidence includes: (i) stellar population



**FIGURE 1.** Left: The SED for J1148+5251 at  $z = 6.42$  from Wang et al. (2009). The UV to mid-IR models are standard low  $z$  quasar SEDs. The FIR through radio model is that for an active star forming galaxy. Middle: The CO excitation in  $z \sim 6$  quasar host galaxies (Wang et al. 2010). Right: The star formation law for nearby and high  $z$  galaxies, including the  $z \sim 6$  quasar host galaxies.

studies of nearby ellipticals, (ii) study of specific star formation rates in galaxies as a function of redshift, and (iii) observation of 'red and dead' ellipticals at  $z \geq 1.5$ . In this context, quasar host galaxies at  $z \sim 6$  represent laboratories for the study of very massive galaxies at the most extreme redshifts.

## FIR luminous quasar host galaxies: Dust and star formation

We have a long-standing program to study the thermal emission from warm dust in large samples of quasars from  $z \sim 2$  to 6, using (sub)mm bolometer cameras such as MAMBO (Wang et al. 2009). We find that about 1/3 of high redshift quasar host galaxies are hyper-luminous IR galaxies ( $L_{\text{FIR}} \sim 10^{13} L_\odot$ ), and that this fraction is roughly constant with redshift out to  $z \sim 6$ . The implied dust masses are of order  $10^8 M_\odot$ . In this paper, we concentrate on the 33 quasars at  $z > 5.7$  to 6.4, comprising all the quasars known at these redshifts as of 2008.

The detection of large dust masses within 1Gyr of the Big Bang immediately raises an interesting question: how to form so much dust so early? The standard dust formation mechanism in the ISM involves coagulation in the cool winds from low mass stars (Draine 2003), which, naively would take too long ( $\geq 10^{9.3}$  years; although cf. Venkatesan et al. 2006). The large dust masses have led to a number of theoretical studies of early dust formation, with models ranging from dust formation associated with massive star formation in eg. supernova remnants (Dwek et al. 2007), to dust formation in outflows from the broad line regions of quasars (Elvis et al. 2002). Recent observations of the UV-extinction curves in a few  $z \sim 6$  quasars and GRBs suggest a different dust composition at these very high redshift quasars relative to the Milky Way or the SMA, as well as relative to quasars at  $z < 4$ . The extinction can be modeled by larger silicate and amorphous carbon grains (vs. eg. graphite), as might be expected from dust formed in supernova remnants (Stratta et al. 2007 Perley et al. 2010). The formation of dust in the early Universe remains an interesting open question.

We have performed extensive studies of the SEDs of the  $z \sim 6$  quasars from rest frame

UV to radio wavelengths, with reasonable sampling of the rest frame FIR. Figure 1a shows the results for the most distant quasar known, J1148+5251 at  $z = 6.42$ . Through the rest frame mid-IR the SED is consistent with the standard low  $z$  quasar templates. However, in the FIR, these mm-detected quasars show a clear excess above the low  $z$  quasar template. The FIR excess can be reasonably fit with dust at 50K. Extrapolating into the radio, we find that the SEDs of these sources are consistent with the radio–FIR correlation for star forming galaxies (Yun et al. 2001). Based on this result, as well as similar circumstantial evidence from molecular gas and FSL emission below, we conclude that the host galaxies are undergoing a major starburst episode, co-eval with the AGN. The implied star formation rates are  $\sim 10^3 \text{ M}_\odot \text{ year}^{-1}$ .

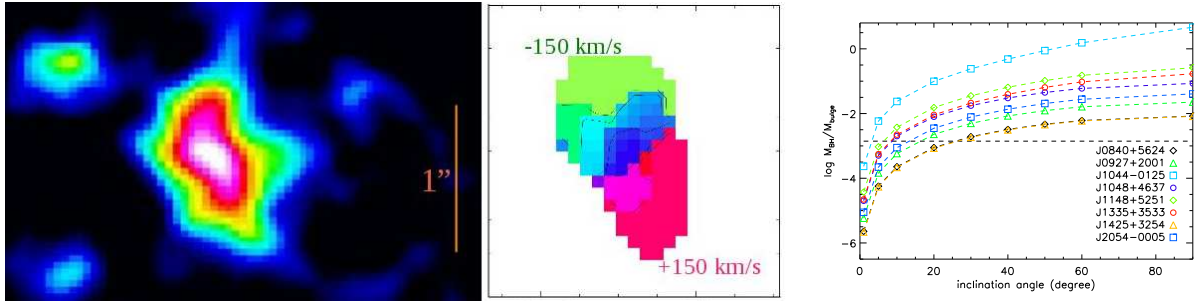
### Molecular gas: the fuel for star formation

We have searched for CO emission in 8 FIR-luminous  $z \sim 6$  quasars host galaxies, and we detect the molecular gas in all cases (Wang et al 2010). The implied molecular gas masses are  $\sim 10^{10}(\alpha/0.8) \text{ M}_\odot$ , and line widths range from  $200 \text{ km s}^{-1}$  to  $800 \text{ km s}^{-1}$ .

We have observations of multiple CO transitions in a number of the  $z \sim 6$  quasars (Figure 1b). The CO is highly excited, consistent with constant brightness temperature ( $S_\nu \propto \nu^2$ ) up to CO 5-4, at least. Standard radiative transfer modeling (LVG) implies warm ( $\geq 50\text{K}$ ), and dense ( $\sim 10^4 \text{ cm}^{-3}$ ) molecular gas. Gas at this density is only seen in the star forming cores of GMCs in the Milky Way, on scales  $\sim 1\text{pc}$ . In the case of the quasars, we find these conditions persist on kpc-scales.

We have investigated the integrated relationship between gas mass and star formation for the  $z \sim 6$  quasar host galaxies using the standard ‘Kennicutt-Schmidt’ law, ie. the relationship between CO luminosity and FIR luminosity (or surface brightness; Figure 1c)). A correlation between CO and FIR luminosity has been well established for nearby galaxies, as well high redshift star forming galaxies (Gao & Solomon 2004). The  $z \sim 6$  quasar host galaxies fall within the scatter in this relationship, as defined by the star forming galaxy populations. The origin of this relationship has been extensively discussed in the literature. Herein, we make two simple points. First, the fact that the quasar hosts fall within the established relationship is further circumstantial evidence for star formation. And second, the relationship is non-linear, with a power-law index of 1.5. This implies a decreasing gas consumption timescale with increasing luminosity. The quasar hosts would consume all of their molecular gas in  $10^7$  years at the current star formation rates, as compared to eg. the Milky Way, for which the gas consumption timescale is 30 times longer.

Interferometric arrays allow for high resolution imaging of the molecular gas in these distant galaxies. Figure 2a shows the CO distribution and kinematics for J1148+5251 at  $z = 6.42$  at  $0.3''$  resolution (Walter et al. 2004). The molecular gas extends to a radius of at least  $\sim 3\text{kpc}$ . Higher resolution observations ( $0.15''$ ) show two high  $T_B$  peaks (35K) with sizes  $\sim 1\text{kpc}$ , separated by  $\sim 2\text{kpc}$ , each comprising about 1/4 of the total emission. The velocity field implies a dynamical mass within 3 kpc radius of  $5.5 \times 10^{10} \text{ M}_\odot$ . The dynamical mass is within a factor few of the molecular gas mass, suggesting that the inner few kpc of the galaxies are baryon-dominated (as is seen in low  $z$  ellipticals), and



**FIGURE 2.** Left: The CO 3-2 distribution in J1148+5251 derived from VLA observations (Walter et al. 2004; 2003). Center: the CO 7-6 velocity field of J1148+5251 derived from PdBI observations (Riechers et al. 2010, in prep). Right: The black hole – bulge mass ratio for the  $z \sim 6$  quasars as a function of assumed inclination angle for the disk (Wang et al. 2010). The dash line represents the low  $z$  ratio.

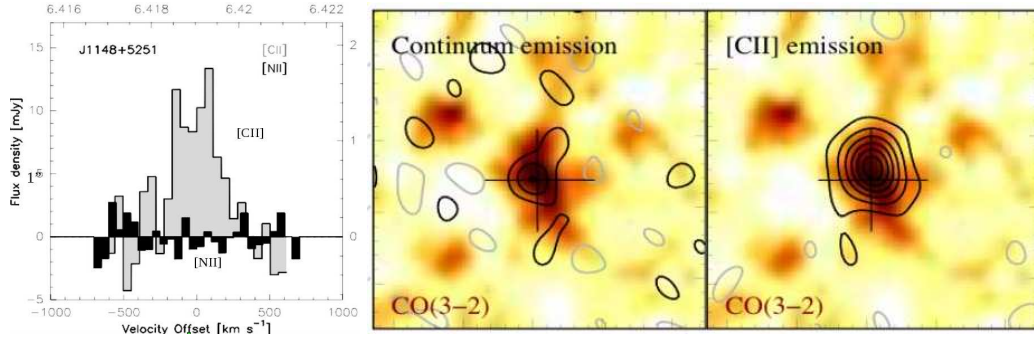
that the molecular gas comprises a substantial fraction of the dynamical mass ( $\sim 10\%$  to  $50\%$ ).

High resolution imaging of gas dynamics allows for study of the evolution of the black hole – bulge mass relation at high redshift. Indeed, these CO observations present the only method in the near term to perform such a test in the most distant galaxies. Imaging of a few  $z \geq 4$  quasars shows a systematic departure from the low  $z$  relationship (Riechers et al. 2008; 2009; Walter et al. 2004). Wang et al. (2010) find that, assuming random inclination angles for the molecular gas, the  $z \sim 6$  quasars are, on average, a factor 15 away from the black hole – bulge mass relation, in the sense of over-massive black holes. Alternatively, all of the  $z \sim 6$  quasars could be close to face-on, with inclination angles relative to the sky plane all  $< 20^\circ$  (Figure 2c). High resolution imaging of the CO emission from these systems is required to address the interesting possibility that the black holes form before the host spheroids.

### Fine structure lines: a maximal starburst disk

Atomic fine structure line emission, and in particular, the [CII]  $158 \mu\text{m}$  line, is thought to be the dominant ISM gas cooling line, tracing the CNM and photon-dominated regions associated with star formation (Cormier et al. 2010). These lines require space observations to be studied in nearby galaxies, however, at high redshift, the lines redshift into the submm, and hence can be studied with existing ground-based telescopes. We have started a systematic search for [CII] emission from  $z > 6.2$  quasar host galaxies using the PdBI. Thus far, we have three detections of the [CII] line, including J1148+5251 (Figure 3a). One [CII] detection is for a quasar which is not detected in submm continuum emission. Generally, recent results on [CII] emission from high  $z$  star forming galaxies suggest a broad scatter in the [CII]/FIR ratio, by about two orders of magnitude.

Figure 3b shows images of the [CII] emission from J1148+5251 at  $0.25''$  resolution from the PdBI (Walter et al. 2009). The [CII] emission is extended over about 1.5 kpc. If [CII] traces star formation, the implied star formation rate per unit area  $\sim 10^3 \text{ M}_\odot \text{ year}^{-1} \text{ kpc}^{-2}$ . This value corresponds to the predicted upper limit for a ‘maximal starburst disk’



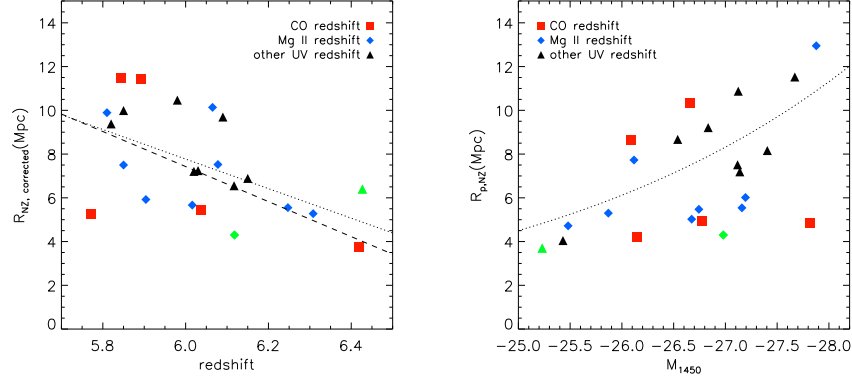
**FIGURE 3.** Left: the [CII] 158  $\mu\text{m}$  spectrum of J1148+5251, plus an upper limit for [NII] 205  $\mu\text{m}$  from the PdBI (Maiolino et al. (2005). Right: PdBI imaging of the dust and [CII] emission (contours, left and right, respectively) at 0.25'' resolution, plus the VLA CO 3-2 in greyscale (Walter et al. 2009).

by Thompson et al. (2005), ie. a self-gravitating gas disk that is supported by radiation pressure on dust grains. Such a high star formation rate areal density has been seen on pc-scales in Galactic GMCs, as well as on 100 pc scales in the nuclei of nearby ULIRGs. For J1148+5251 the scale for the disk is yet another order of magnitude larger.

### Quasar near-zones

Fan et al. (2006) present evidence for ionized regions, or quasar near-zones (NZ), surrounding  $z \sim 6$  quasars on Mpc-scales, presumably caused by radiation from the quasars ionizing the local (partially neutral) IGM. The evidence is in the form of excess emission in the wing of the  $\text{Ly}\alpha$  line leaking to lower redshift due to the ionization of the immediate environs of quasar. Their analysis suggests a decrease in the size of these spheres from  $z = 5.7$  to 6.4, qualitatively consistent with an increase in the neutral fraction of the IGM over this narrow redshift range. However, the Fan et al. study had inaccurate host galaxy redshifts (based, predominantly, on UV emission lines), and had a limited sample size.

We have improved on the analysis using a sample of 27 quasars between  $z = 5.7$  to 6.4, include more sources than previous studies, and more accurate redshifts for the host galaxies, with 8 CO molecular line redshifts and 9 MgII redshifts. We confirm the trend for an increase in NZ size with decreasing redshift, with the luminosity normalized proper size evolving as:  $R_{\text{NZ,corrected}} = (7.4 \pm 0.3) - (8.0 \pm 1.1) \times (z - 6)$  Mpc. While derivation of the absolute IGM neutral fraction remains difficult with this technique, the evolution of the NZ sizes suggests a decrease in the neutral fraction of intergalactic hydrogen by a factor  $\sim 9.4$  from  $z = 6.4$  to 5.7, in its simplest interpretation. Alternatively, recent numerical simulations suggest that this rapid increase in near-zone size from  $z = 6.4$  to 5.7 is due to the rapid increase in the background photo-ionization rate at the end of the percolation or overlap phase of cosmic reionization, when the average mean free path of ionizing photons increases dramatically (Bolton et al. 2010). In either case, the results are consistent with the idea that  $z \sim 6$  to 7 corresponds to the tail end of cosmic reionization. The scatter in the normalized NZ sizes is larger than



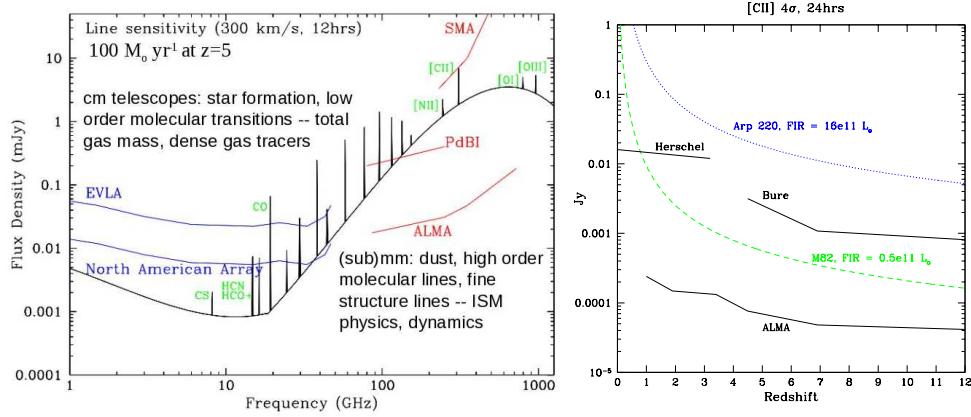
**FIGURE 4.** Left: Radii of the luminosity normalized quasar near zones versus redshift (Carilli et al. 2010). The long dash line show a weighted linear fit to the data with  $R_{\text{NZ,corrected}} = (7.4 \pm 0.3) - (8.0 \pm 1.1) \times (z - 6)$ . Right: The relationship between  $R_{\text{p,NZ}}$  and  $M_{1450}$ . The dotted line is not a fit to the data, but shows the relationship:  $R_{\text{NZ}} \propto \dot{N}_Q^{1/3} \propto 10^{-M_{1450}/7.5}$ , as expected for photo-ionization by the quasars.

expected simply from measurement errors, and likely reflects intrinsic differences in the quasars or their environments. We find that the near-zone sizes increase with quasar UV luminosity, as expected for photo-ionization by quasar radiation.

## Conclusions: ALMA and EVLA

Overall, the study of  $z \sim 6$  quasars suggest massive starbursts in the host galaxies of the FIR luminous sample, ie. co-eval formation of a massive galaxy and a supermassive black hole within 1 Gyr of the Big Bang. Li et al. (2007) have investigated this possibility using their large volume cosmic structure formation simulation. They select the most massive halo in the  $3 \text{ cGpc}^3$  volume, and follow the formation of the galaxy and supermassive black hole, starting at  $z = 14$ . They find that a massive galaxy can form by  $z \sim 6$  through a series of gas rich mergers, driving the formation rates over  $10^3 M_\odot \text{ year}^{-1}$  at times. The  $10^9 M_\odot$  black hole also forms via Eddington limited accretion and black hole mergers. The system should eventually evolve into a giant elliptical galaxy at the center of a massive cluster of galaxies. One caveat is that that the duty-cycle must be high, ie. the galaxy has been active for much of the time since  $z = 14$ . Further key observations to test these ideas include: (i) a search for the expected companion galaxies in the clusters, and (ii) observations of the stellar population of the host galaxy.

Our studies demonstrate the power of radio observations to study the dust, gas, and (obscuration-free) star formation in the first galaxies. However, we are currently limited to the most active, massive galaxies at these high redshifts. Fortunately, the EVLA and ALMA are both close to completion, opening a new window into the the study of the first galaxies. Figure 7 shows the capabilities for studying the line emission from distant star forming galaxies. The EVLA, with its sensitivity and broad fractional bandwidth, will allow for large cosmic volume, blind surveys for molecular gas in early galaxies.



**FIGURE 5.** Left: the spectrum of an active star forming galaxy at  $z = 5$  plus the sensitivity of the current and future interferometers. Right: the expected [CII] line peak flux density versus redshift for active and dwarf star forming galaxies, plus the sensitivity of ALMA and other instruments.

Likewise, the two orders of magnitude improvement in submm sensitivity with ALMA enables the study of the fine structure lines and dust in normal star forming galaxies ( $\text{SFR} \sim 1 \text{ to } 10 M_{\odot} \text{ year}^{-1}$ ) well into cosmic reionization ( $z \sim 6 \text{ to } 10$ ).

ALMA and the EVLA represent an order of magnitude, or more, improvement in most observational capabilities from  $1 \text{ GHz}$  to  $1 \text{ THz}$ . These facilities provide a powerful new tool to study the 'other half of galaxy formation.'

- Bolton, J.S. et al. *MNRAS*, in press (2010)  
 Carilli, C.L. et al. *ApJ* **714**, 834 (2010)  
 Cormier et al. *A&A* in press (2010)  
 Draine, B. *ARAA* **41**, 241 (2003)  
 Dwek, E. et al. *ApJ* **662**, 927 (2007)  
 Elvis, M. et al. *ApJ* **567**, L107 (2002)  
 Fan, X. et al. *AJ* **632**, 117 (2006)  
 Gao, Y. & Solomon, P. *ApJ* **606**, 271 (2004)  
 Häring, N. & Rix, W. *ApJ* **604**, L89 (2004)  
 Li, Y. et al. *ApJ* **665**, L187 (2007)  
 Maiolino, R. et al. *A&A* **40**, L51 (2005)  
 Perley, D. et al. *ApJ* in press (2010)  
 Riechers, D. et al. *ApJ* **690**, 463 (2009)  
 Riechers, D. et al. *ApJ* **686**, L9 (2008)  
 Stratta, G. et al. *ApJ* **661**, L9 (2007)  
 Thompson, T. et al. *ApJ* **630**, 167 (2005)  
 Venkatesan, A. et al. *ApJ* **640**, 31 (2006)  
 Walter, F. et al. *Nature* **457**, 699 (2009)  
 Walter, F. et al. *ApJ* **615**, L17 (2004)  
 Walter, F. et al. *Nature* **424**, 406 (2003)  
 Wang, R. et al. *ApJ* **714**, 699 (2010)  
 Wang, R. et al. *ApJ* **687**, 848 (2008)  
 Willott, C. et al. *AJ* **139**, 906 (2010)  
 Yun, M.S. et al. *ApJ* **554**, 803 (2001)